Magnetic Sensor
Analog linear output type
HGARAP001A
Design Guide

Document No: 830P0058-O
Nov. 2024 Rev1.0

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Analog Linear Output Type Magnetic Sensor HGARAP001A

Alps Alpine high-precision magnetic sensors use Giant Magneto Resistive effect (GMR) for horizontal magnetic fields detection. Utilizing the GMR element for its high output and exceptional resistance to high temperatures and magnetic fields, our sensors achieve high output level and sensitivity compared to other GMR sensors; approximately 100 times higher than Hall element and 10 times higher than AMR element based on our research.

We offer various magnetic sensors for dedicated usage such as non-contact switch applications, linear position detection and angle detection as well as rotational speed and direction sensing in response to external magnetic fields. This document provides essential information for understanding and implementing Analog Linear Output Type Magnetic Sensor (herein after magnetic angle sensor) in your design. Please note that HGARAP001A is Magnetic Angle sensor without built-in amplifier.

1. Overview

This product is a magnetic sensor based on highly sensitive and accurate GMR magnetic detection element. It is widely used as a horizontal magnetic field detection sensor in automobiles, industrial equipment, home appliances, games, portable devices, and other fields. It can detect linear position, angle, rotation speed and direction based on external magnetic field, and is especially suitable for the field of rotation angle detection.

Application example

- **Energy industry**
  - Motor Rotation Detection
  - Robot joint and arm angle detection
  - Movement detection during linear stroke
- **Game, VR-AR**
  - Joystick angle
  - Paddle position
- **Medical**
  - Angle detection for nursing bed
  - Motor rotation detection for infusion pump
- **Automotive**
  - Motor rotation detection (EPS, EV main power motor, oil pump)
  - Angle detection for pedal lever (steering wheel, pedal, valve)

Feature

- The sensor device that detects the rotation angle of a magnet by GMR magnetic technology.
- Compared with Hall, AMR, and TMR sensors, it has higher waveform stability and high precision with an error of less than 0.05 degrees after compensation.
- Detects only the horizontal magnetic field angle and not affected by changes in the magnetic field strength.
- 2-phase signals for sin and cos can be output regardless of the magnetization interval.
- Allows front-to-back and side-to-side configuration of the magnet.
- Highly robust to magnet and sensor gap changes.
- Various microcontroller can be combined with external amplifier. Sensor bridge resistor is 1.75k ohm.

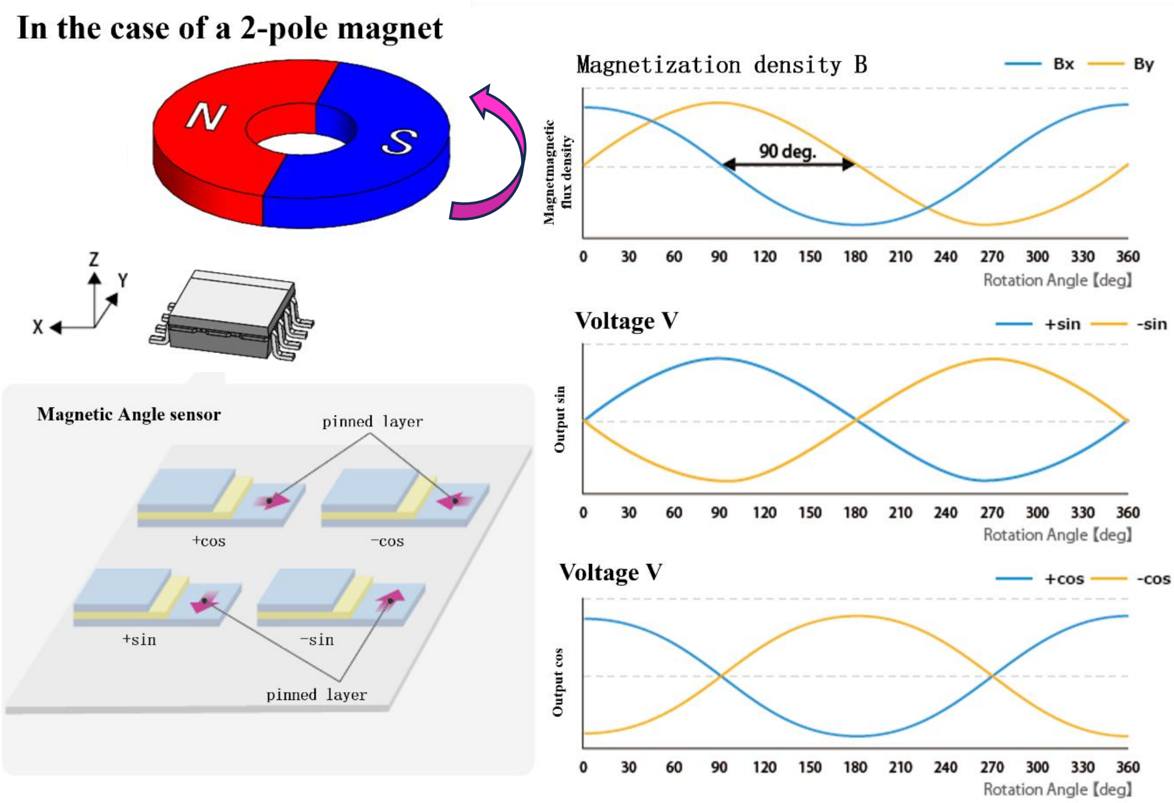


Fig.1 Output signal of magnetic angle sensor

2. Angle calculation for magnetic angle sensor

The process

The magnetic angle sensor (HGARPS011A) has four MR sensor bridges in the package and the four sensor bridges output two phase signals with a phase difference of 90 degrees.

① The magnetic angle sensor output four analog signal such as +sin, -sin, +cos and -cos.

② Obtain the value for sin and cos by calculating the difference between +sin and -sin also +cos and -cos. Depend on necessity amplify (or attenuate) the signal level.

③ Angle can be obtained by calculation using the value sin and cos. Absolute angle range: 0 to 360deg

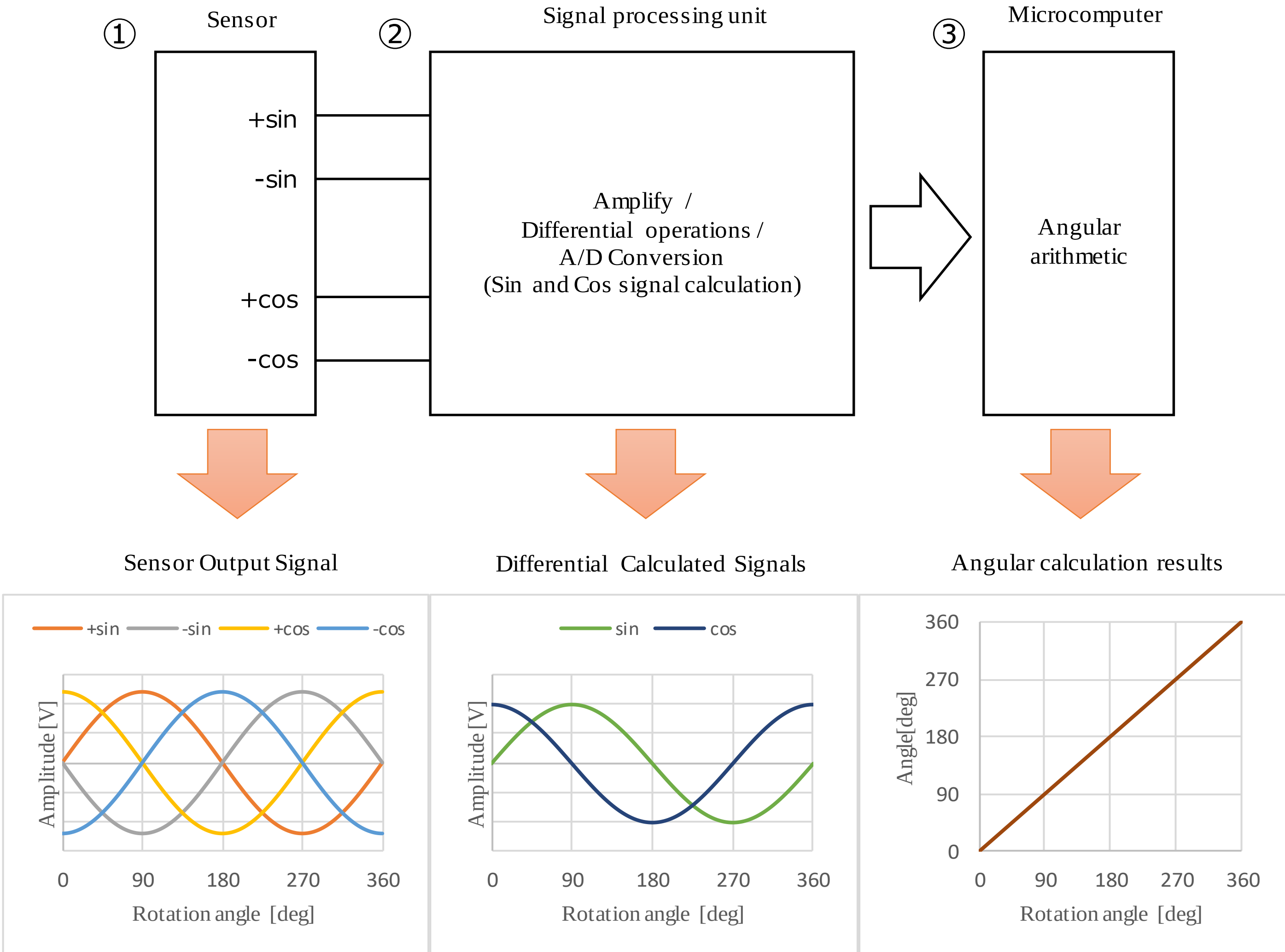
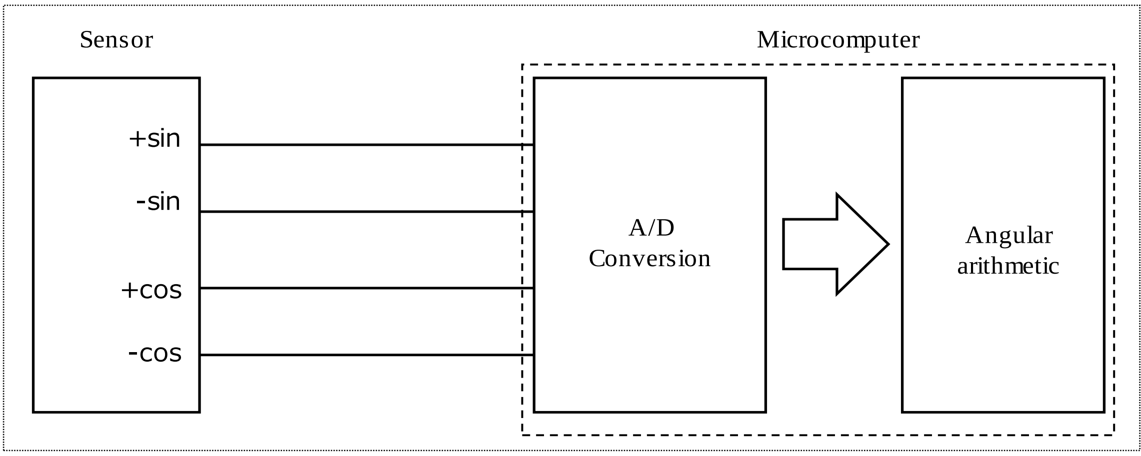


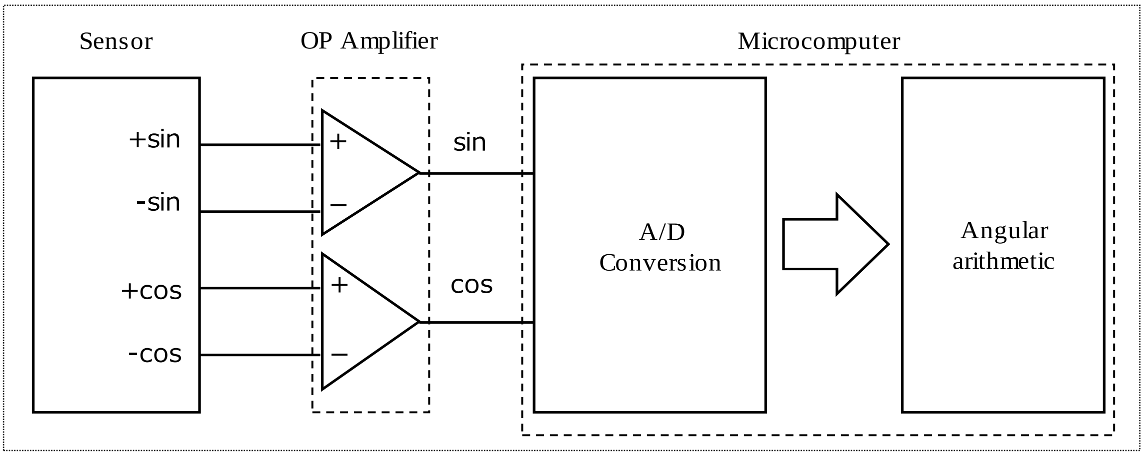
Fig.2 Angle calculation flow

Structure examples for angle calculation system (reference only)

(i)Configuration to generate sin and cos signals after A/D conversion of sensor output signals



(ii)Configuration for A/D conversion after generating analog sin and cos signals



(iii)Configuration in which the sensor output signal is converted to A/D by the ADC and then sin and cos signals are generated

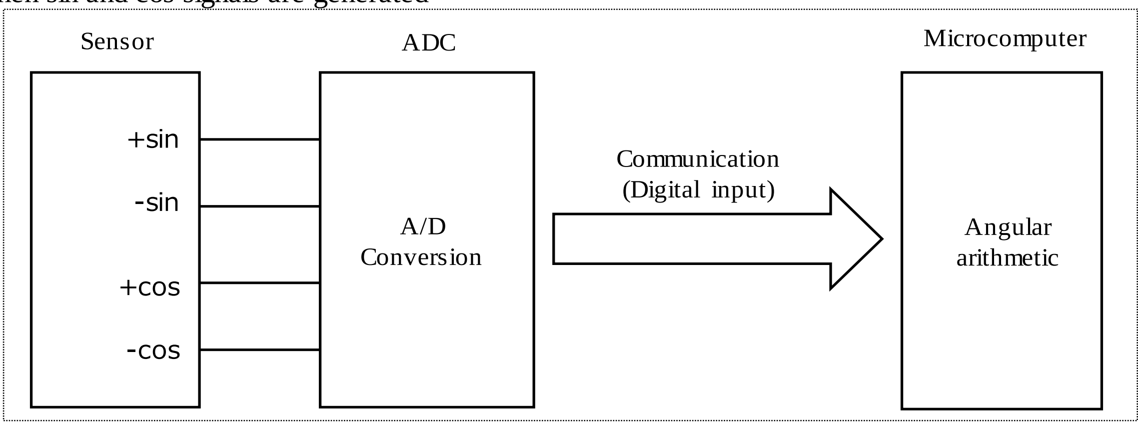


Fig.3 Examples for system structure

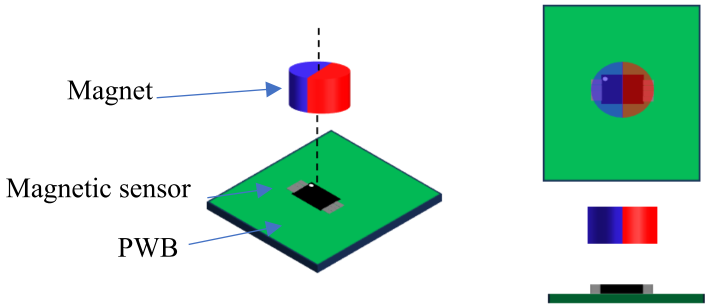
<u>Sensor layout to the magnet</u>

2-pole magnet (column type or ring type) is recommended as Fig. 4.

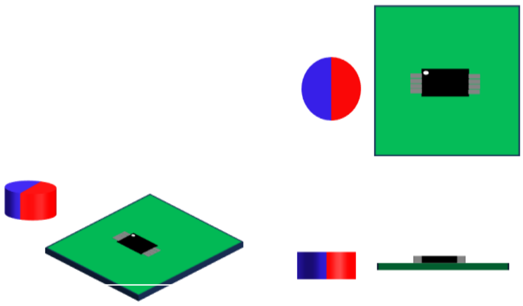
Ring type 2-pole　　Column type 2-pole

Fig.4 shape of magnet

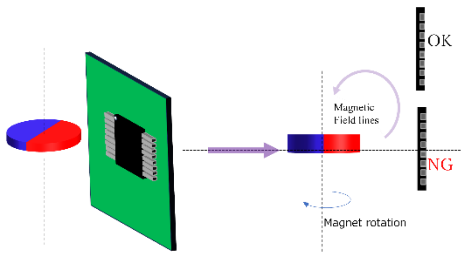
Some variations of layout are available between the sensor and the magnet (Fig. 5).



<Align with magnet center axis>



<Side on magnet type-A (horizontal)>



*To avoid dead area (non-detection area), layout must be set carefully.

<Side on magnet type-B (vertical)>

Fig.5 Layout of magnetic angle sensor

3. Design example

This section describes an example of a working design for a magnet perpendicular to a magnetic angle sensor when the following types of magnets are used.

Condition

Magnet type: Ferrite 2-pole ring shaped magnet

Magnet size: 10mm in diameter

Sensor layout: Shaft end of magnet

Magnet field strength: 50mT

- **Target of magnet field strength**

Adjust the layout of the magnet and the magnetic angle sensor to ensure that the magnetic field strength ranges from 20mT to 60mT. As shown in Fig.7, the output voltage will almost saturate when the magnetic field strength is about 10mT or more, while it will stabilize at 100% output at 20mT or more. However, if the magnetic field strength exceeds 60mT, waveform distortion may result and too strong a magnetic field may damage the sensor.

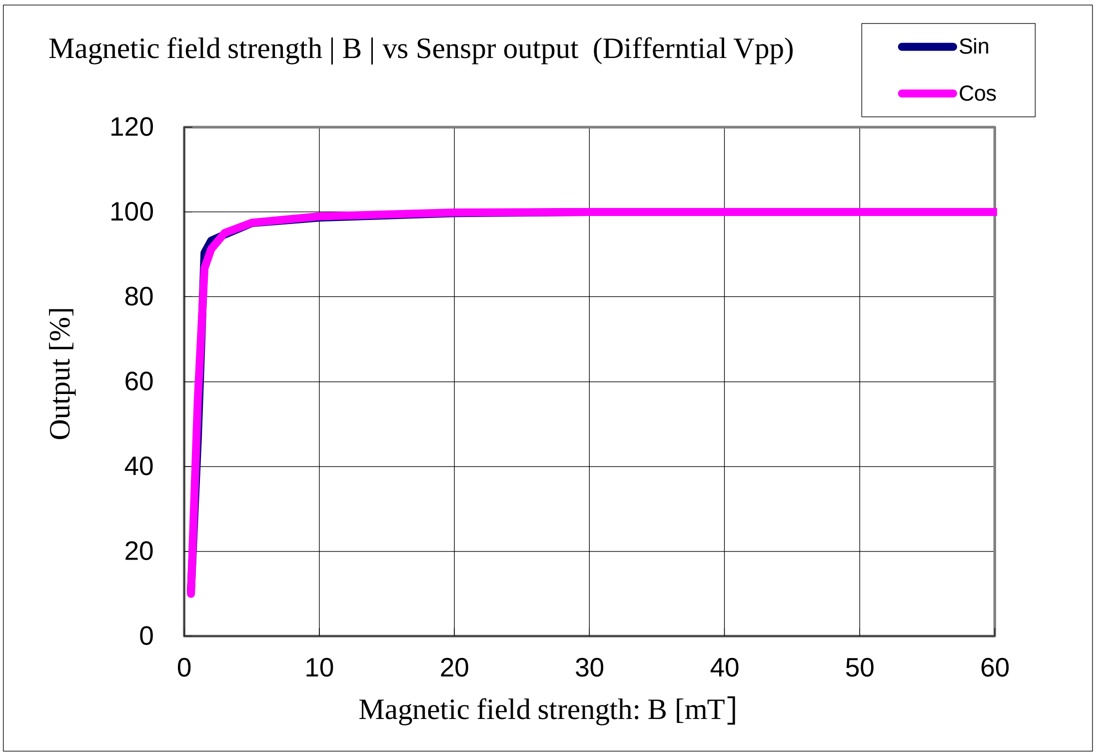


Fig.6 Sensor output character (@VDD 5V)

Circuit design

Fig.7 shows reference circuit for magnetic angle sensor.

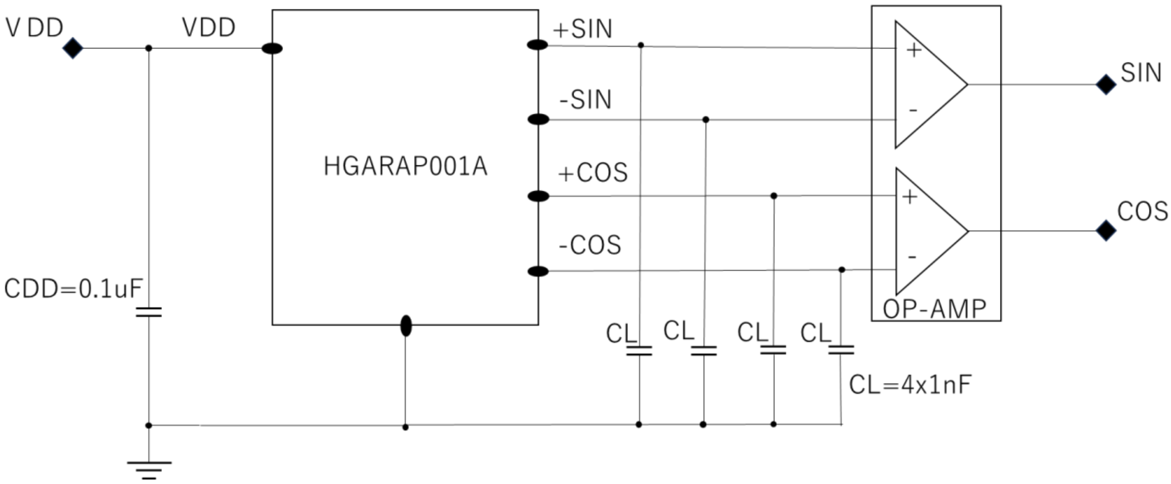


Fig.7 Reference circuit for magnetic angle sensor

Parameters

Supply voltage	VDD=3.3V
Bypass Capacitor (VDD)	CDD=0.1uF
Bypass Capacitor (Output)	CL=1nF

Add suitable capacitor CL in your design. It is recommended that you set the capacity of CL to 10nF or less. Since adding capacitance to the sensor output may cause oscillation or waveform distortion. Be sure to decide the value of CL in the actual design.

4. Angle calculation method

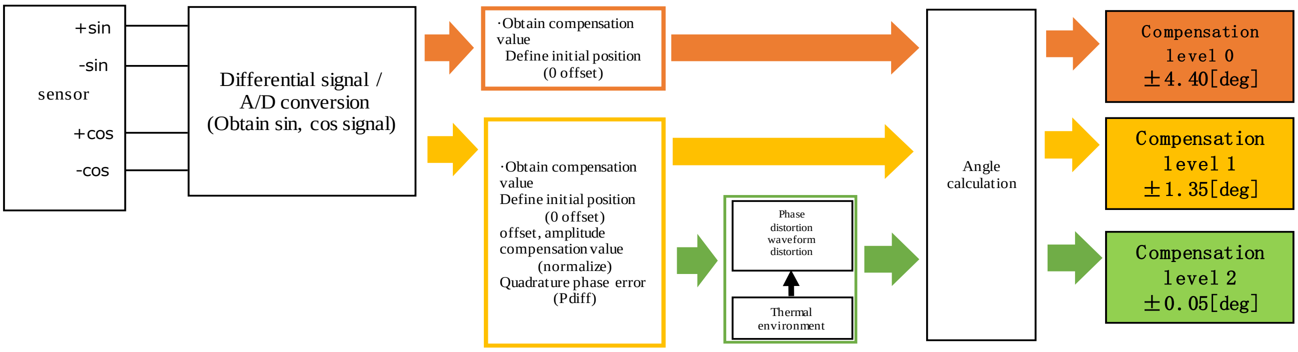
Generally following 2 types of method are available for angle calculation.

- Calculation method
- Table transform method

Obtaining accurate angle with magnetic angle sensor requires eliminating error factors that affect the results. These error factors include variations in the characteristics of the sensor, asymmetry in the polarity of the magnet's N and S poles, and tolerance of position between the sensor and the magnet. Althoug it is very difficult to completely eliminate these factors in a realistic environment, the accuracy of angle detection can be improved by a simple compensation process.

In the calculation method, different level of compensation calculations can be selected depending on the user's desired accuracy. We provide an evaluation kit that allows you to try the compensation calculation of level 1 (Refer to the evaluation kit manual (HGARPS011A)).

The calculation method provides 3 levels of compensation. Following is the processing of compensation.



※ Results in our experimental environment

Fig.8 Compensation flow at desired level

In addition to the calculation method, compensation can be possible by creating a compensation table (Look Up Table). By obtaining an angular error profile beyond the 360-degree range and performing a pre-calculation of the angle by an arbitrary compensation process. The result of the calculation is made into a compensation table, which is written to an EPROM. The result of the angle calculation can be obtained directly at each calculation without performing angle calculation.

5. Description of the angle calculation

The angle can be calculated by following the different compensation levels step by step.

Compensation procedure for the calculation method

Compensation level can be selected depend on necessity. The next section describes the method of angle calculation using the arithmetic method.

Compensation level 0

Step 1. AD conversion for sin and cos differential signal

Obtain AD converted V(sin) and V(cos) from sensor differential signal such as +sin,-sin,+cos and -cos.
(Please note that the method of acquiring differential signals may vary depend on the circuit structure)

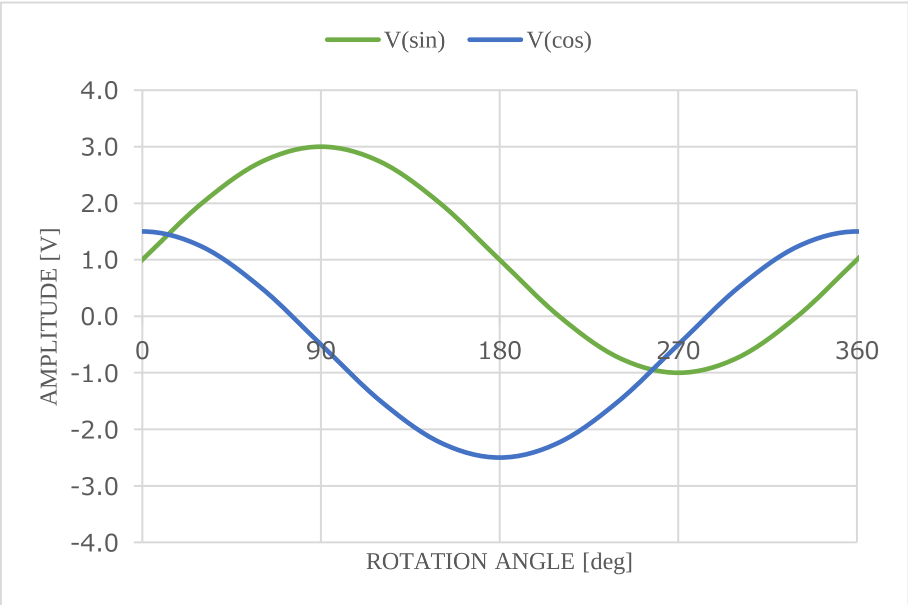


Fig.9 sin and cos signals

Step 2. Define initial position: Zero angle0 [deg]

Define initial position (0 deg) as desired.

$$\text{Zero angle0 [deg]} = \text{ATAN2}^{※}(V(\cos), V(\sin)) \times \frac{180}{\pi}$$

(case of V(sin) < 0 : Zero angle0 = Zero angle0 +360deg)

※The ATAN2 function is used to calculate the declination in a Cartesian coordinate.

Step 3. Calculate detected angle: Raw angle [deg]

$$\text{Raw angle [deg]} = \text{ATAN2}(V(\cos), V(\sin)) \times \frac{180}{\pi}$$

(case of V(sin) < 0 : Raw angle = Raw angle +360deg)

Step 4. Calculate detected angle: Lv0 angle [deg]

$$\text{Lv0 angle [deg]} = \text{ATAN2}(V(\cos), V(\sin)) \times \frac{180}{\pi} - \text{Zero angle0}$$

(case of V(sin) < 0 : Lv0 angle = Lv0 angle +360deg)

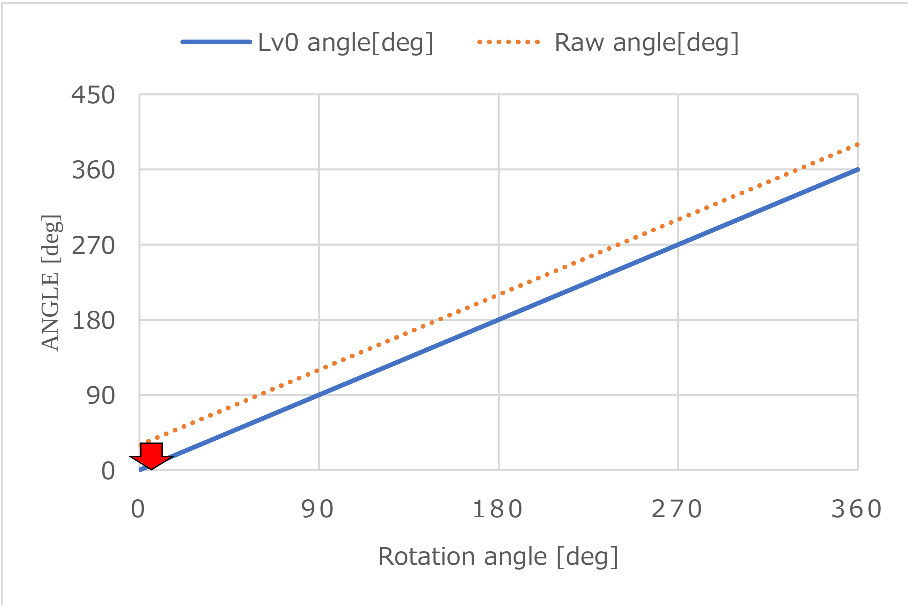


Fig.10 Angle calculation (Zero adjust)

Compensation level 1

Step 1. Obtaining max/min values

Obtain max/min values of sin and cos signals from one cycle data. Rotate the magnet 360 degrees to obtain the angle sensor output signal for one cycle.

$V(sin)_{max}$, $V(sin)_{min}$, $V(cos)_{max}$, $V(cos)_{min}$

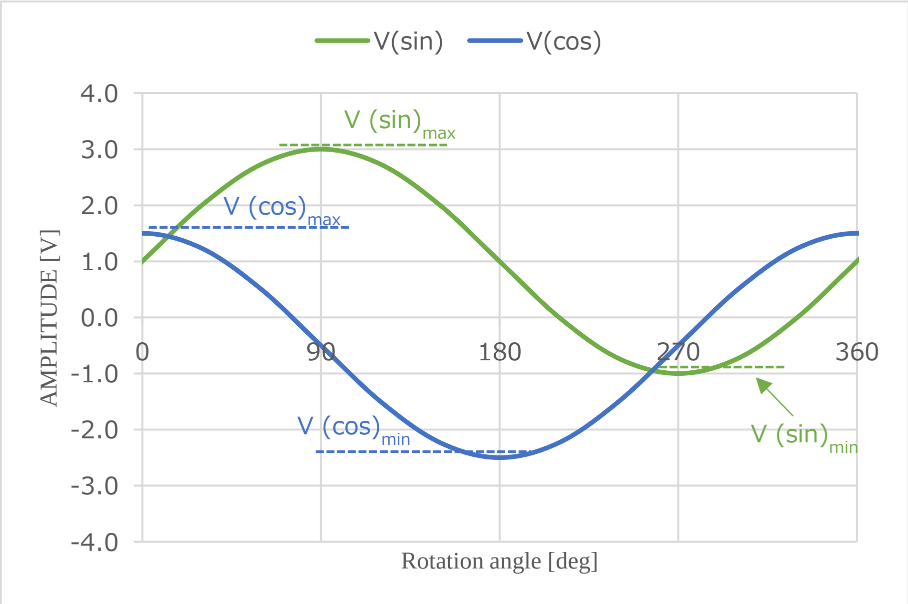


Fig.11 Min/Max value for sin and cos signals

Step 2. Normalize sin and cos signals

Calculate the offset compensation value, amplitude compensation value and use them to normalize the signal to an amplitude of 1 and an offset of 0.

Offset : $\text{Off sin [V]} = \dfrac{V(\sin)_{max} + V(\sin)_{min}}{2}$

$\text{Off cos [V]} = \dfrac{V(\cos)_{max} + V(\cos)_{min}}{2}$

Gain : $\text{Amp sin [V]} = \dfrac{V(\sin)_{max} - V(\sin)_{min}}{2}$

$\text{Amp cos [V]} = \dfrac{V(\cos)_{max} - V(\cos)_{min}}{2}$

$$V_{norm}(\sin)\,[-] = \frac{V(\sin) - \text{Off sin}}{\text{Amp sin}}$$

$$V_{norm}(\cos)\,[-] = \frac{V(\cos) - \text{Off cos}}{\text{Amp cos}}$$

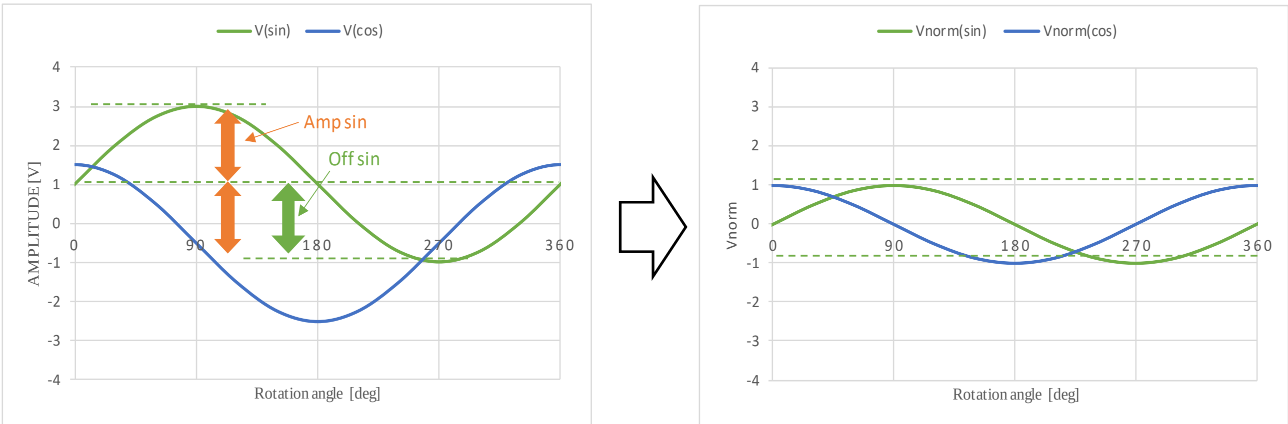


Fig.12 Normalization (Amplitude 1, Offset 0)

Step 3. Calculate P_{diff} (P_{diff}: sin-cos Quadrature phase error)

$$V_{norm}(\sin - \cos) = V_{norm}(\sin) - V_{norm}(\cos)$$

$$V_{norm}(\sin + \cos) = V_{norm}(\sin) + V_{norm}(\cos)$$

Calculate P_{diff} from max value of synthesis wave $V_{norm}(\sin - \cos)_{max}$, $V_{norm}(\sin + \cos)_{max}$

$$P_{diff}[deg] = 1.92*(ATAN\left(\frac{V_{norm}(\sin - \cos)_{max}}{V_{norm}(\sin + \cos)_{max}} \times \frac{180}{\pi}\right) - 45)$$

Step 4. Normalize the signal to an amplitude of 1 and an offset of 0

Calculate the zero angle at initial position (user defined zero position).

$$\text{Zero angle0} = ATAN2^{※}(V(\cos), V(\sin)) \times \frac{180}{\pi}$$

(case of V(sin) < 0 : Zero angle0 = Zero angle0 +360deg)

$$\text{Zero angle1 [deg]} = \text{Norm angle0} - \frac{P_{diff}}{2} - \frac{P_{diff}}{2} \times \sin((2 \times \text{Norm angle0} - 90) \times \frac{\pi}{180})$$

$$\text{Norm angle0 [deg]} = ATAN2(Vnorm(\cos), Vnorm(\sin)) \times \frac{180}{\pi}$$

(case of V_{norm}(sin) < 0 : Norm angle0 = Norm angle0 +360deg)

Calculate the normalized angle.

$$\text{Norm angle [deg]} = ATAN2(Vnorm(\cos), Vnorm(\sin)) \times \frac{180}{\pi} - \overbrace{\text{Zero angle1}}^{\text{Initial position}}$$

(case of V_{norm}(sin) < 0 : Norm angle = Norm angle +360deg)

Step 5. Angle compensation

Calculate the angle with compensation value.

$$\text{Lv1 angle [deg]} = \text{Norm angle} - \frac{P_{diff}}{2} - \frac{P_{diff}}{2} \times \sin((2 \times \text{Norm angle} - 90 + \text{Zero angle1} \times 2) \times \frac{\pi}{180})$$

Compensation level 2

Further compensation can be possible after compensation level 1.

Step 1. Angle compensation

$$\text{Lv2 angle [deg]} = \text{Norm angle} \underbrace{- \frac{P_{diff}}{2} - \frac{P_{diff}}{2} \times \sin\left((2 \times \text{Norm angle} - 90 + \text{Zero angle1} \times 2) \times \frac{\pi}{180}\right)}_{\text{Pdiff correction term } (0^{th} \,\&\, 2^{nd} \text{ order})}$$

$$\underbrace{- \text{Wd2(Temp)} \times \sin(2 \times \text{Norm angle} + \text{Zero angle1} \times 2)}_{\text{waveform distortion correction term } (2^{nd} \text{ order})} \underbrace{- \text{Wd4(Temp)} \times \sin(4 \times \text{Norm angle-180} + \text{Zero angle1} \times 4)}_{\text{waveform distortion correction term } (4^{th} \text{ order})}$$

Note:

Wd2 and Wd4 are defined as follows:

$$\text{Wd2(Temp)} = \left(4.8\times10^{-8} \times (\text{Temp})^3 - 128\times10^{-7} \times (\text{Temp})^2 + 106\times10^{-5} \times (\text{Temp}) - 0.0294\right) \times \left(0.0000074 \times B^2 - 0.001869 \times B + 0.5267\right) / 0.4773$$

$$\text{Wd4(Temp)} = \left(-18\times10^{-4} \times (\text{Temp}) + 0.526\right) \times \left(0.0000074 \times B^2 - 0.001869 \times B + 0.5267\right) / 0.4773$$

Temp: Ambient temperature [deg]

B: Applied magnetic field strength [mT]

Wd2(2nd), Wd4(4th) periodic angle error…coefficient in formula is eigen value of the product.

Compensation procedure for the table transform method

This method is particularly effective when the sensor does not output clear sin and cos signal. As shown in Fig.13, when the sensor is used by placing it on the side of the magnet, the output waveform will be the 3rd harmonic superimposed waveform. Normally compensation based on this waveform would require complex calculations each time. But using the table conversion method, angle calculations can be obtained with simple processing.

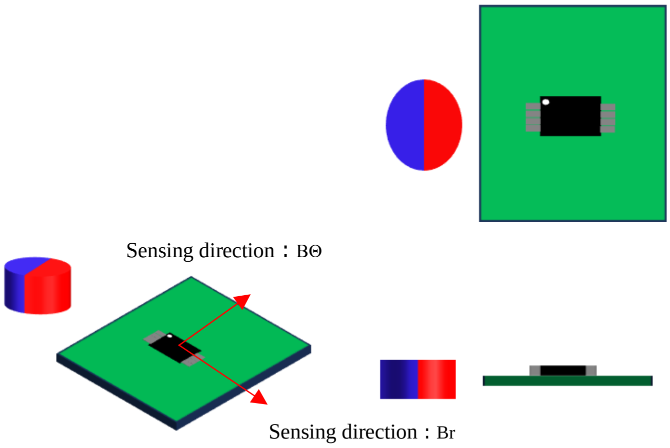


Fig.13 Layout of the magnet

Examples of magnetic strength field and sensor output

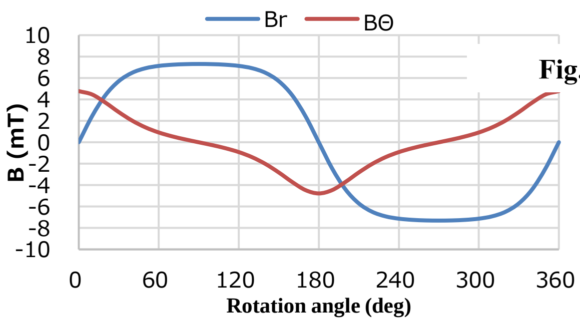


Fig.14 Magnetic strength field near magnet (Br, Bθ)

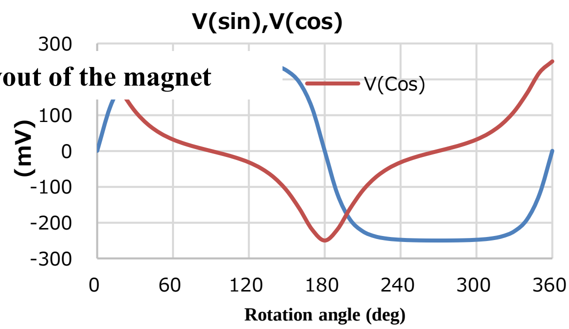


Fig.15 Sensor output

How to create compensation table

Procedure to create simple compensation table is as follows:

Step 1. Define the initial position (0 deg position) as desired.

Step 2. Obtain the angle sensor output signal in one cycle while rotating the magnet 360 degrees at arbitrary angular intervals. If you require the resolution at 1 deg step, 361 data are needed (0 to 360 deg.). In this case absolute angle is necessary in advance.

Step 3. Calculate the angle from sin and cos signals. There are several calculation methods, but simplest is following trigonometric formula:

$$\theta = \tan^{-1} \frac{\sin\theta}{\cos\theta}$$

Step 4. Create a one-to-one correspondence table with the calculation results and absolute angles. This becomes the compensation table.

Step 5. Rotate the magnet to an arbitrary position and obtain the sensor detection angle from the same calculation as in step 3.

Step 6. Correct angle information can be obtained by matching the angle obtained in step 5 with the compensation table.

Step 7. If the corresponding angle does not exist in the compensation table, the angle can be calculated from a linear approximation between the two nearest front and rear points. See below as example.

If the sensor detection angle is 1.9 deg, we can assume it as 2 deg.

If the sensor detection angle is 358.7 deg, there is no matching absolute angle value in the table. In this case a directness approximation calculation is performed using the data from the two points before and after, the detection angles of 358.1 deg and 358.9 deg.

Let y be the absolute angle and x be the detected angle,

$$y = a \times x + b$$

$$358 = 358.1 \times a + b$$

$$359 = 358.9 \times a + b$$

$$a = 1.25, \quad b = -89.625$$

$$y = 1.25 \times x - 89.625$$

Therefore, absolute angle should be 358.75 deg.

Absolute angle [deg]	Detection angle [deg]
0	-0.1
1	0.8
2	1.9
3	3.0
⋮	⋮
357	357.3
358	358.1
359	358.9
360	359.6

Document No: 830P0058-O
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6. General precautions

The following are general precautions for using magnetic sensors and magnets.

Selecting the appropriate magnet

Select the type and strength of the magnet in accordance with the specification of the magnetic sensor and the requirements of the application scenario. Excessive strength of the magnet may cause the sensor to malfunction.

Thermal environment

Magnets are sensitive to temperature and the strength of the magnetic field varies with temperature. When the magnetic sensor and magnet are heated, the stability of the magnetic field may be affected. Therefore it is necessary to investigate appropriate thermal countermeasures.

Influence of Magnet Configuration and Surrounding Magnetic Materials

Magnetic sensors are affected by surrounding magnetic materials (e.g. magnets, iron). Check whether the interference of the magnetic field affects the operating performance of the magnetic sensor and take care to adjust the magnet, the surrounding magnetic material and the sensor to the appropriate positional relationship.

Static electricity

Magnetic sensors are semiconductor devices. They can be damaged by static electricity that exceeds the capacity of the specified electrostatic protection circuit. Take adequate measures to protect against static electricity during use.

EMC

Magnetic sensors may be damaged or malfunction due to over-voltage of the power supply in an automobile environment, exposure to radio waves, and so on. Implement protection measures (Zener diodes, capacitors, resistors, inductors, etc.) as necessary.

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Revision history

Date	Version	Change
Nov. 12 2024	1.0	Layout release (English version)